Use of Head-Tail Chromaticity Monitor for the LHC.

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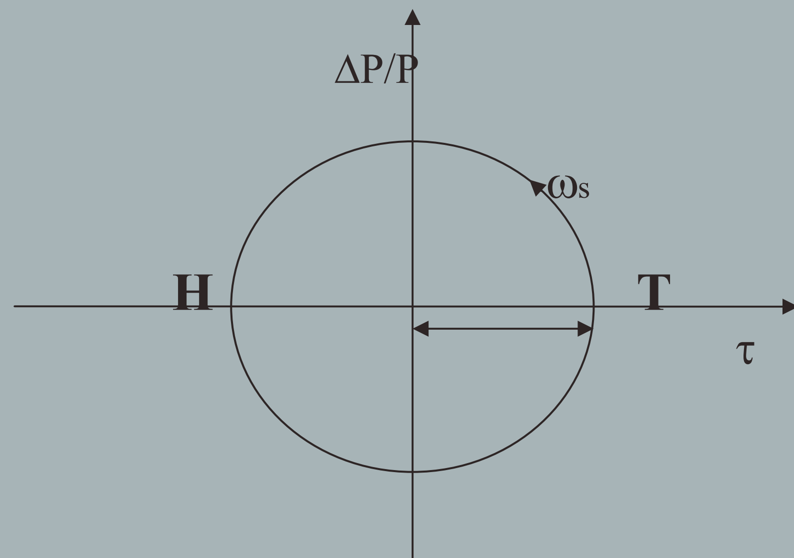
Overview

- *Introduction to Head-Tail Phase Shift method to measure chromaticity*
- *Set-up of H-T monitor in the Tevatron*
  - *Limitation of system in Tevatron.*
- *Measurement issues in the LHC*
- *Other possible uses of the H-T monitor:*
  - *Fitting Wake fields, 2nd order Chromaticity*

Longitudinal Beam Dynamics



Longitudinal ‘phase-space’ Graph

$$\delta(s) = \frac{-2\pi q_s}{\eta C} r \sin(2\pi q_s s / C + \varphi)$$

$$z(s) = r \cos(2\pi q_s s / C + \varphi)$$

Chromaticity Measurement Using Head-Tail Phase Shift

In the presence of non-zero chromaticity the betatron frequency is perturbed by:

$$\omega_\beta(\delta) = \omega_{\beta 0} + \omega_0 \xi \delta$$

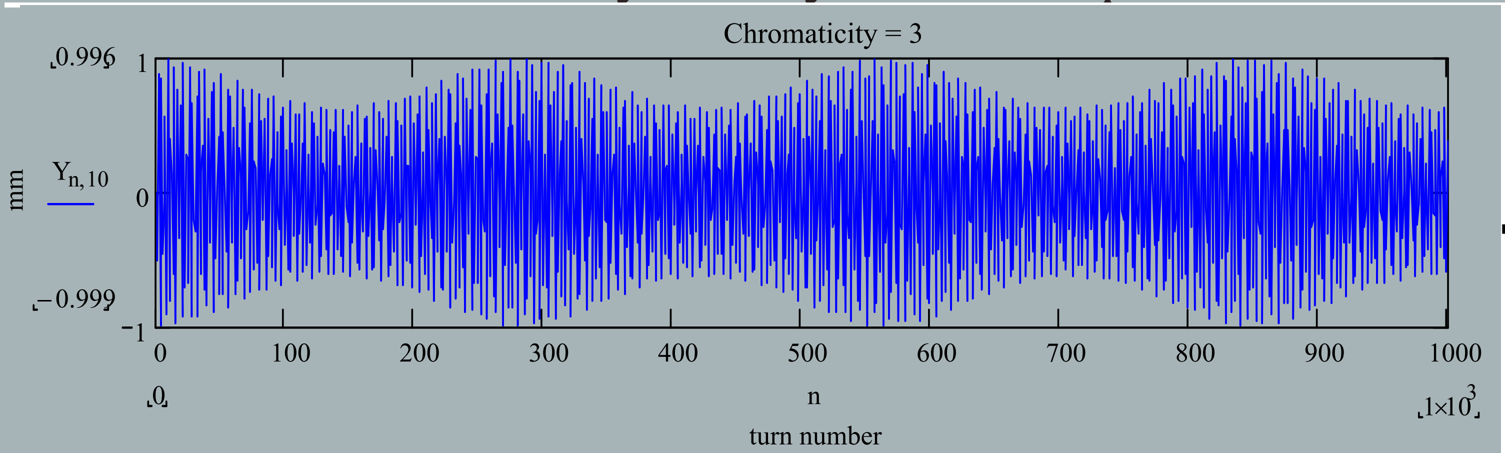
the equation of motion per particle becomes:

$$A \exp[\pm i(2\pi Q n + \frac{\xi \omega_0}{\eta} \tau (1 - \cos(2\pi q_s n)) + \frac{\delta \xi}{q_s} \sin(2\pi q_s n))]$$

Which when integrated over a guassian δ distribution gives[1]:

$$Y(\xi, \tau, n) = e^{-\frac{\omega_0{}^2 \xi^2 \sigma_\tau{}^2}{2\eta^2} \sin^2(2\pi q_s n)} \sin\left[2\pi Q n + \frac{\omega_0 \xi}{\eta} \tau (1 - \cos(2\pi q_s n))\right]$$

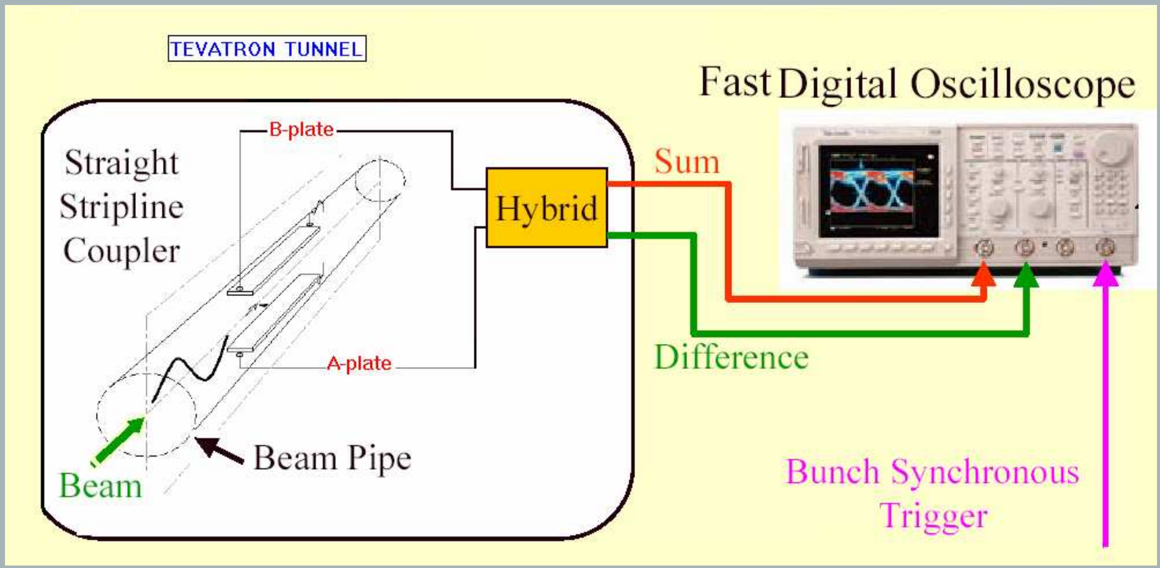
The result of this simple model predicts a beam envelope which recoheres every half synchrotron period.



And a phase which recoheres every full synchrotron period reaching a maximum phase difference every half synchrotron period. Thus from the phase difference between two locations in a bunch the chromaticity can be calculated using:

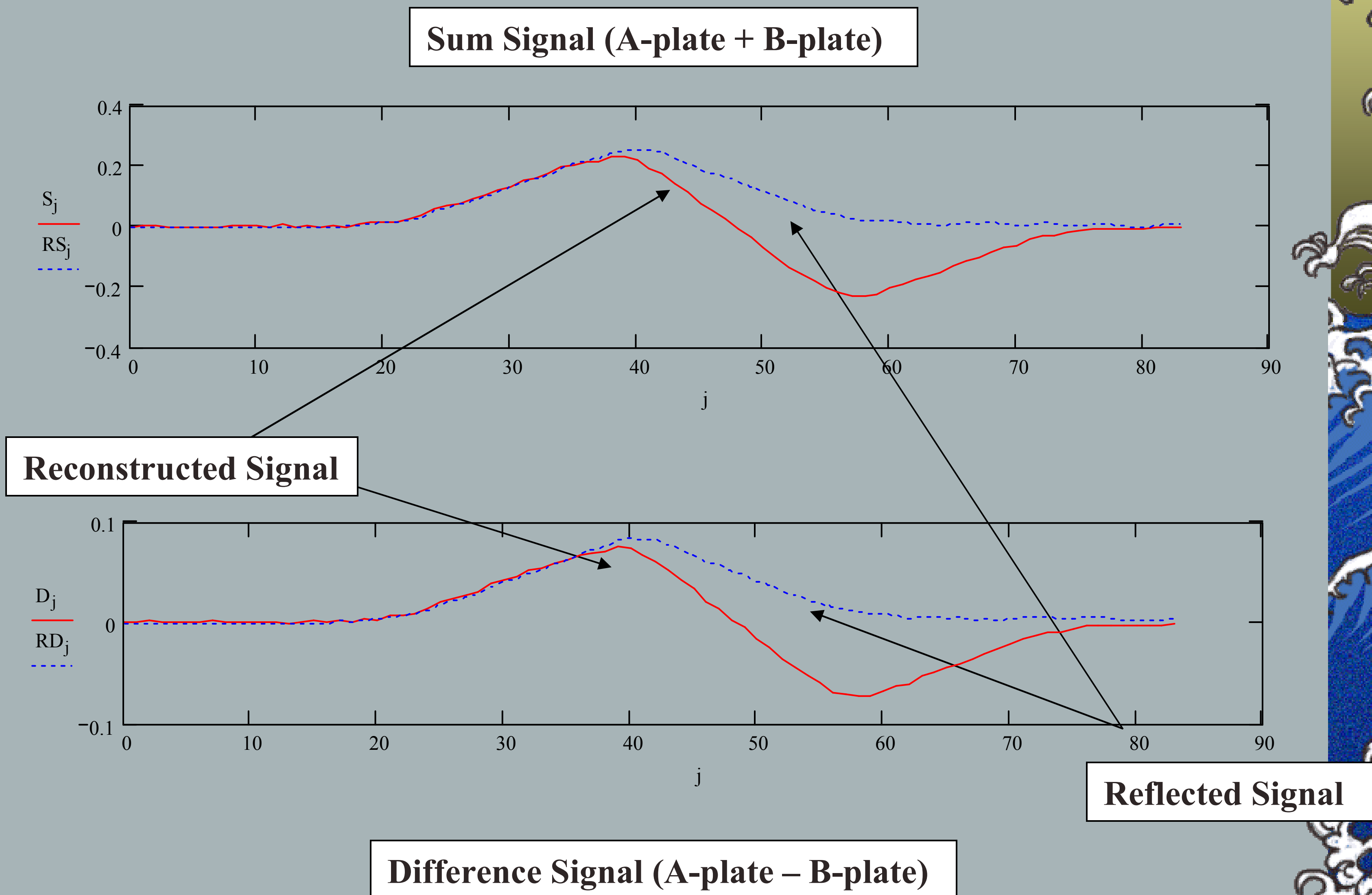
$$\xi = -\eta \frac{\Delta\Psi}{\omega_o \Delta\tau(\cos(2\pi n q_s) - 1)}$$

Extracting Transverse position

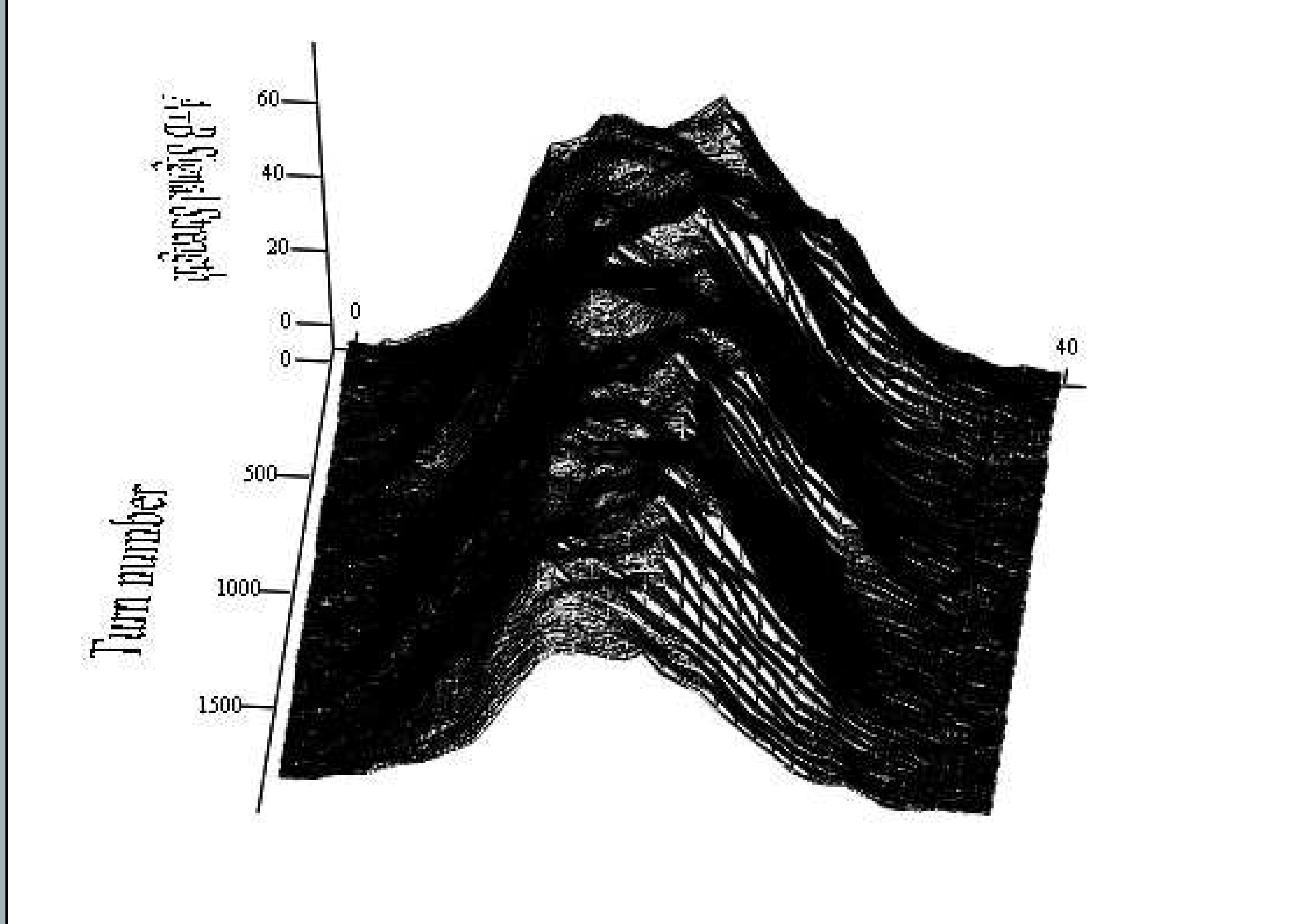


Using the vertical and horizontal strip-line detectors installed in the Tevatron at the F0 location we extract a profile of the transverse behavior of the beam over a single longitudinal bunch.

The Raw Signal is Processed to remove the Reflected Signal using analog deconvolution



Turn by Turn Sum(A+B) Profile from Strip-line monitor



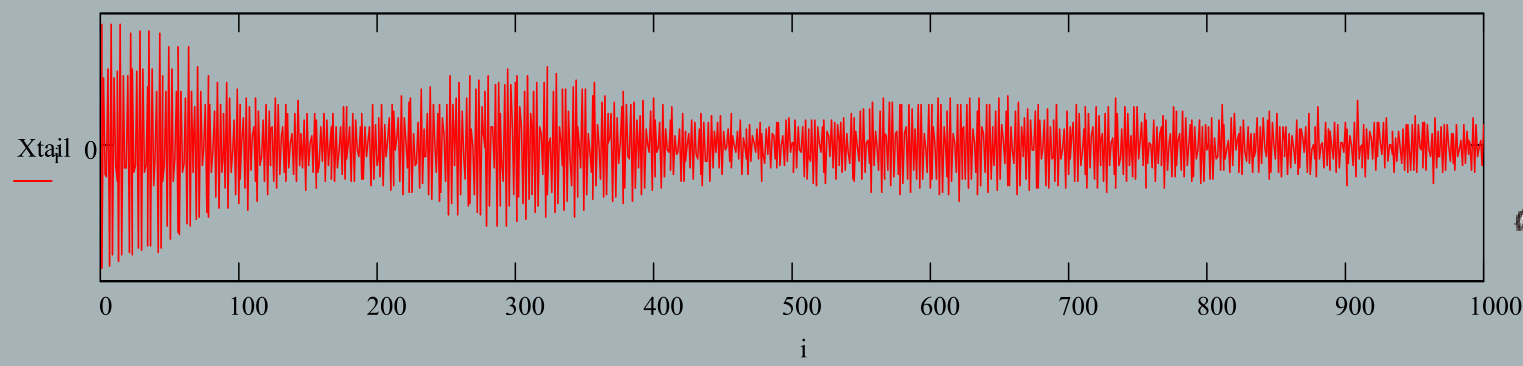
S

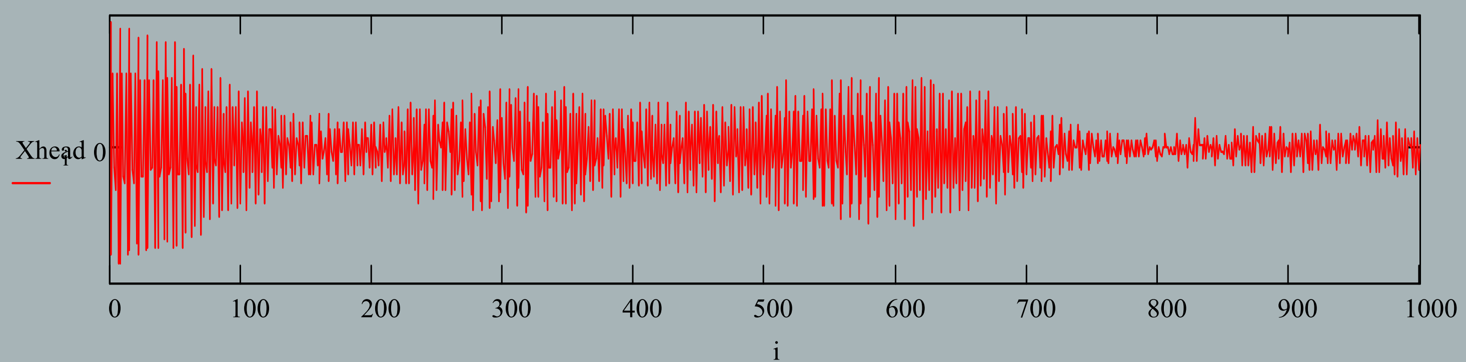
From the Sum and Difference (A-plate ± B-plate) Signals the Transverse position can be calculated using:

$$X(n,\tau) = 27 \times G \cdot \frac{Difference\left(A(n,\tau) - B(n,\tau)\right)}{Sum\left(A(n,\tau) + B(n,\tau)\right)}$$

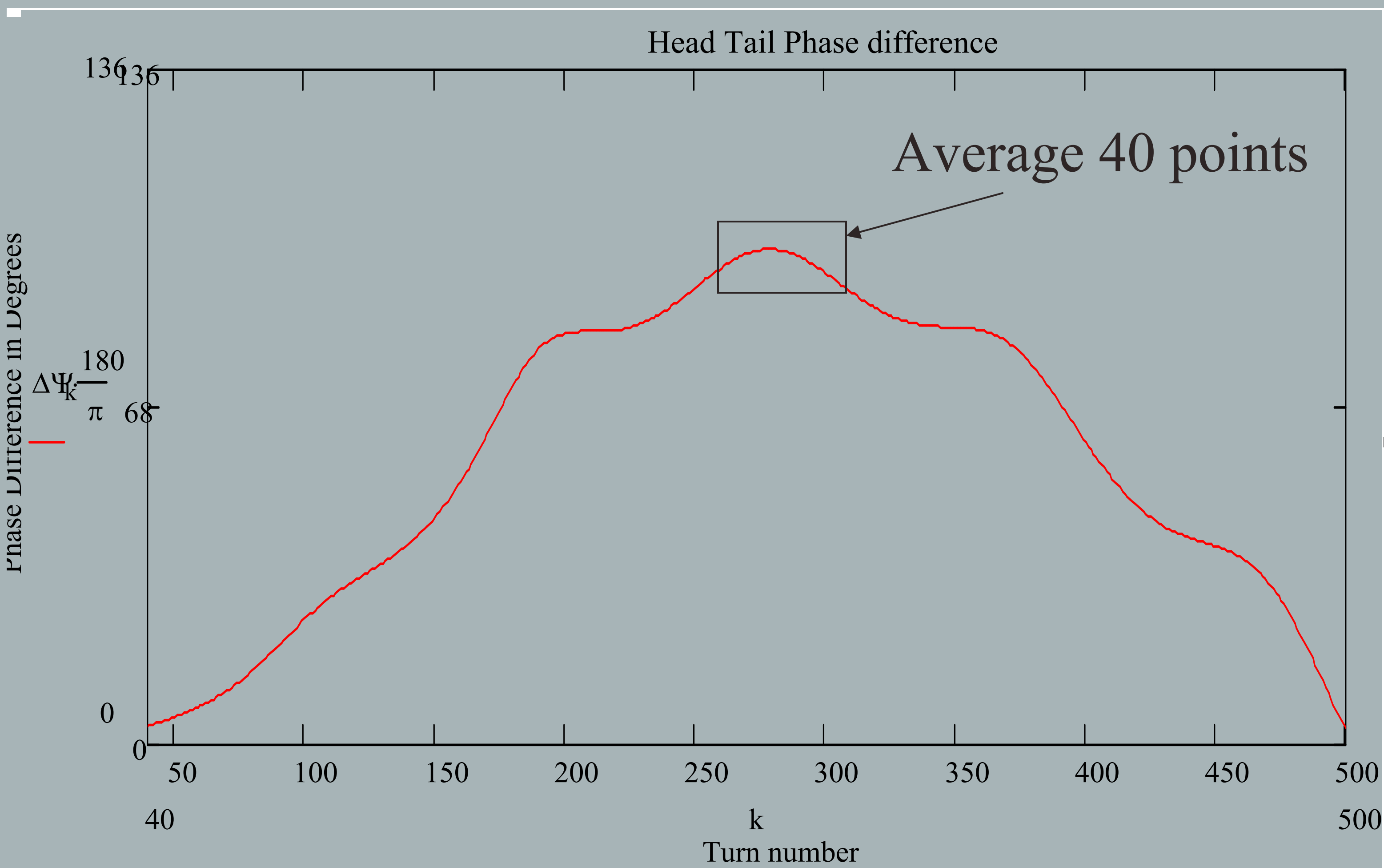
Here G is the ratio of the A-B gain over the A+B gain.Once the Transverse Position as a function of longitudinal bunch position is known (τ) we can use this to analyze the phase shift between the Head and the Tail to Calculate Chromaticity.

Vertical turn by turn position after vertical 1.6 mm kick. Head and Tail are separated by .8 nsecs



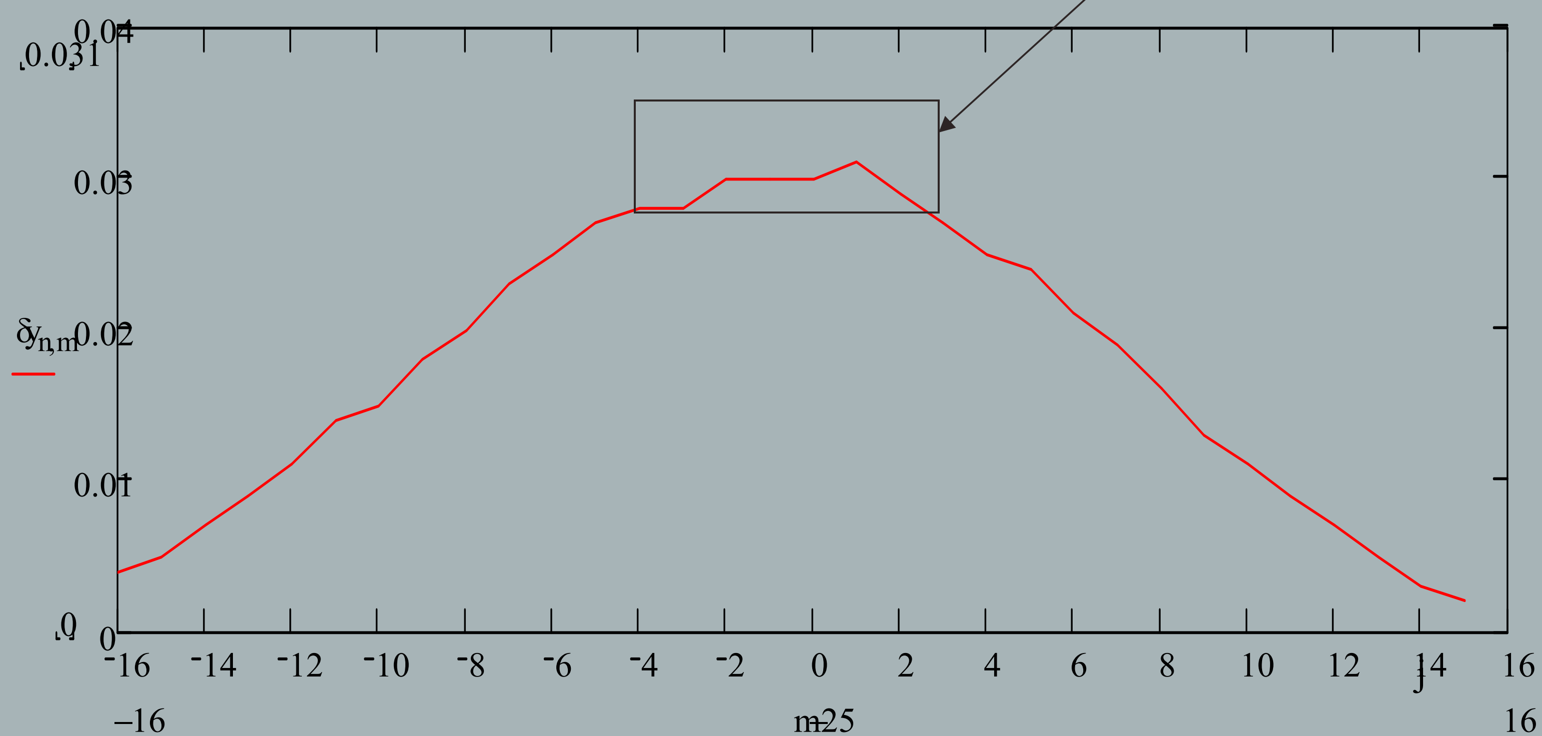


Head Tail Phase Evolution for Chromaticity = 5 units

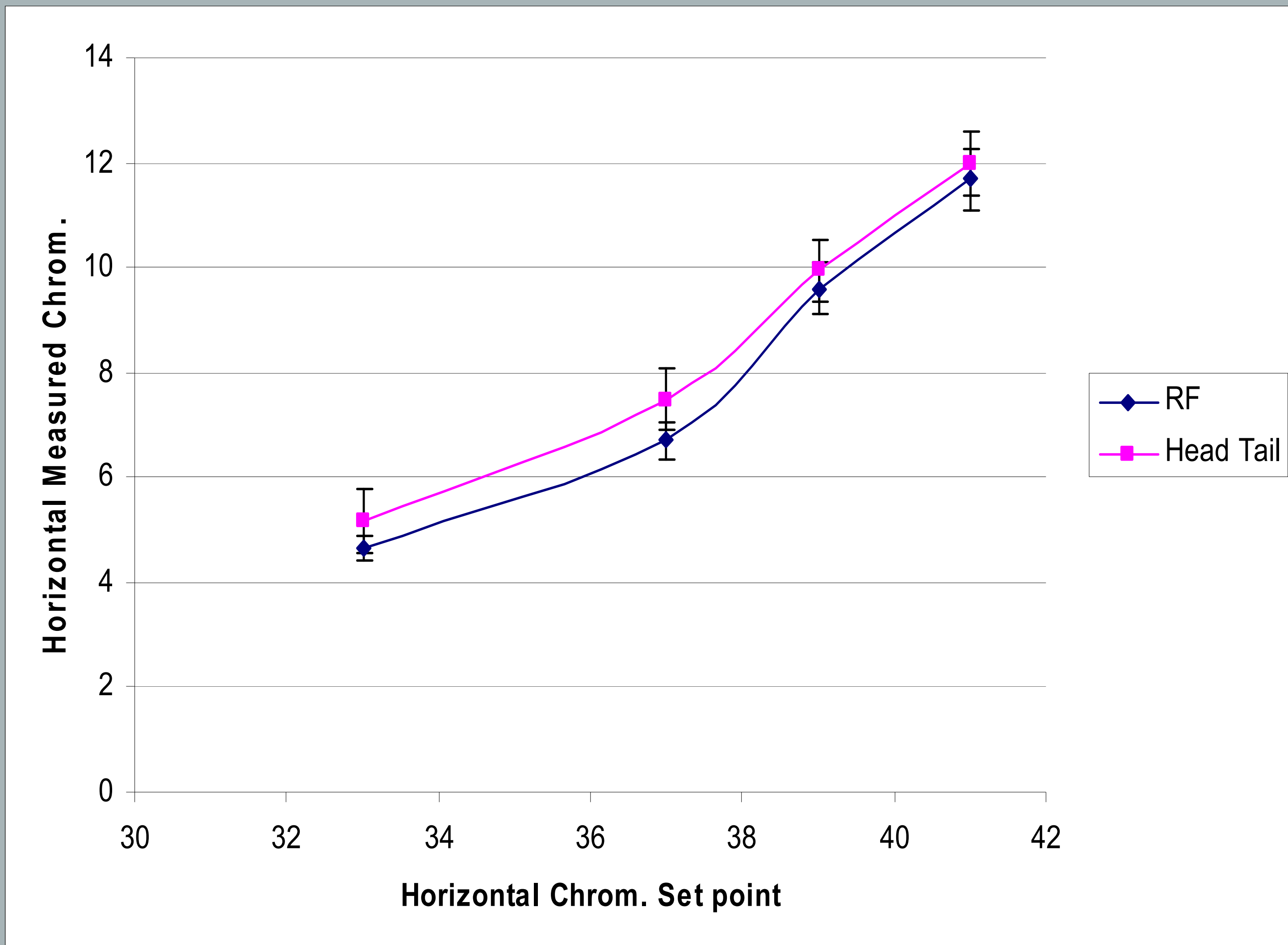


Then we take total of 7 bunch slices around the bunch center and take phase differences between head and tail points, then average them all

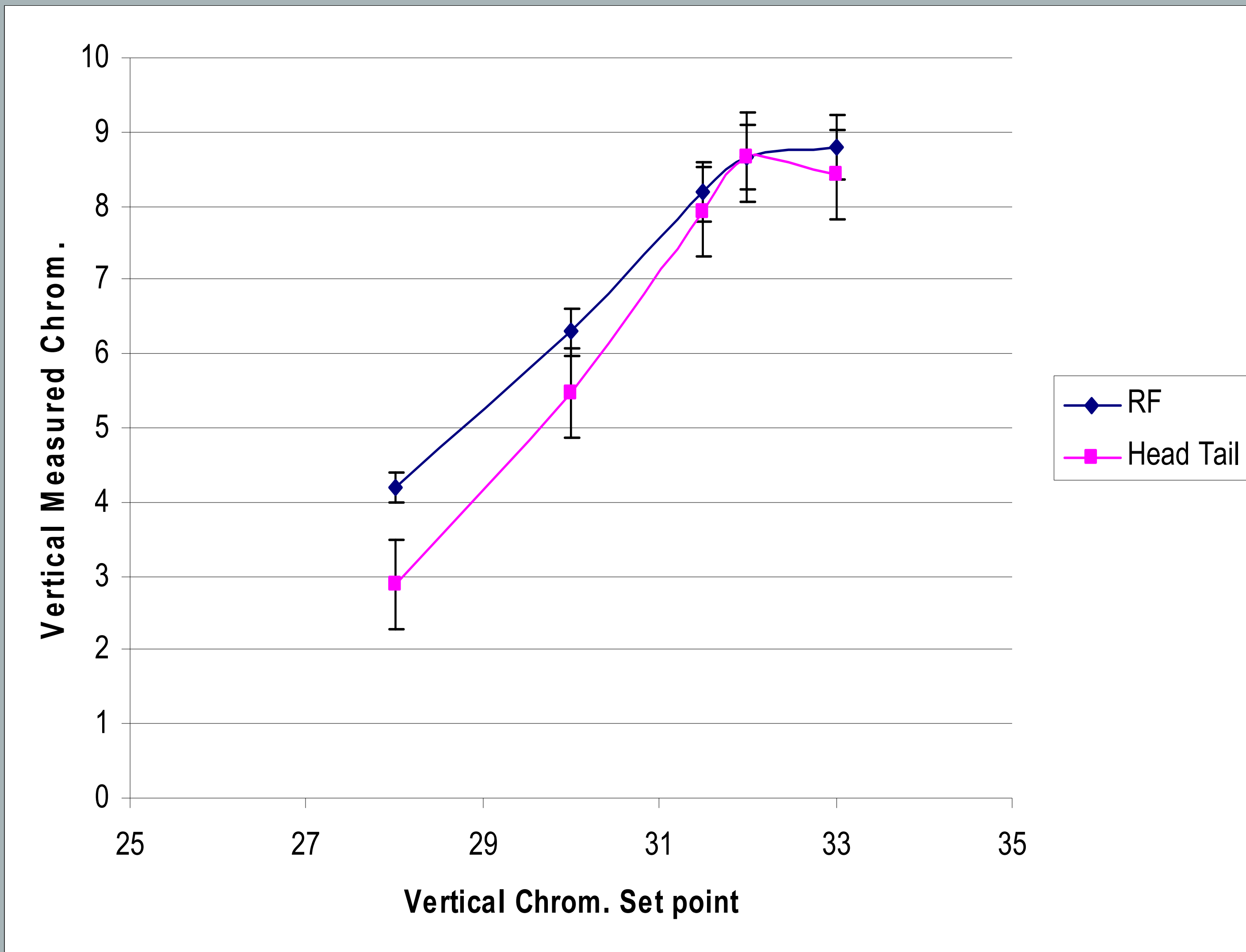
Take 3 points on either Side of bucket



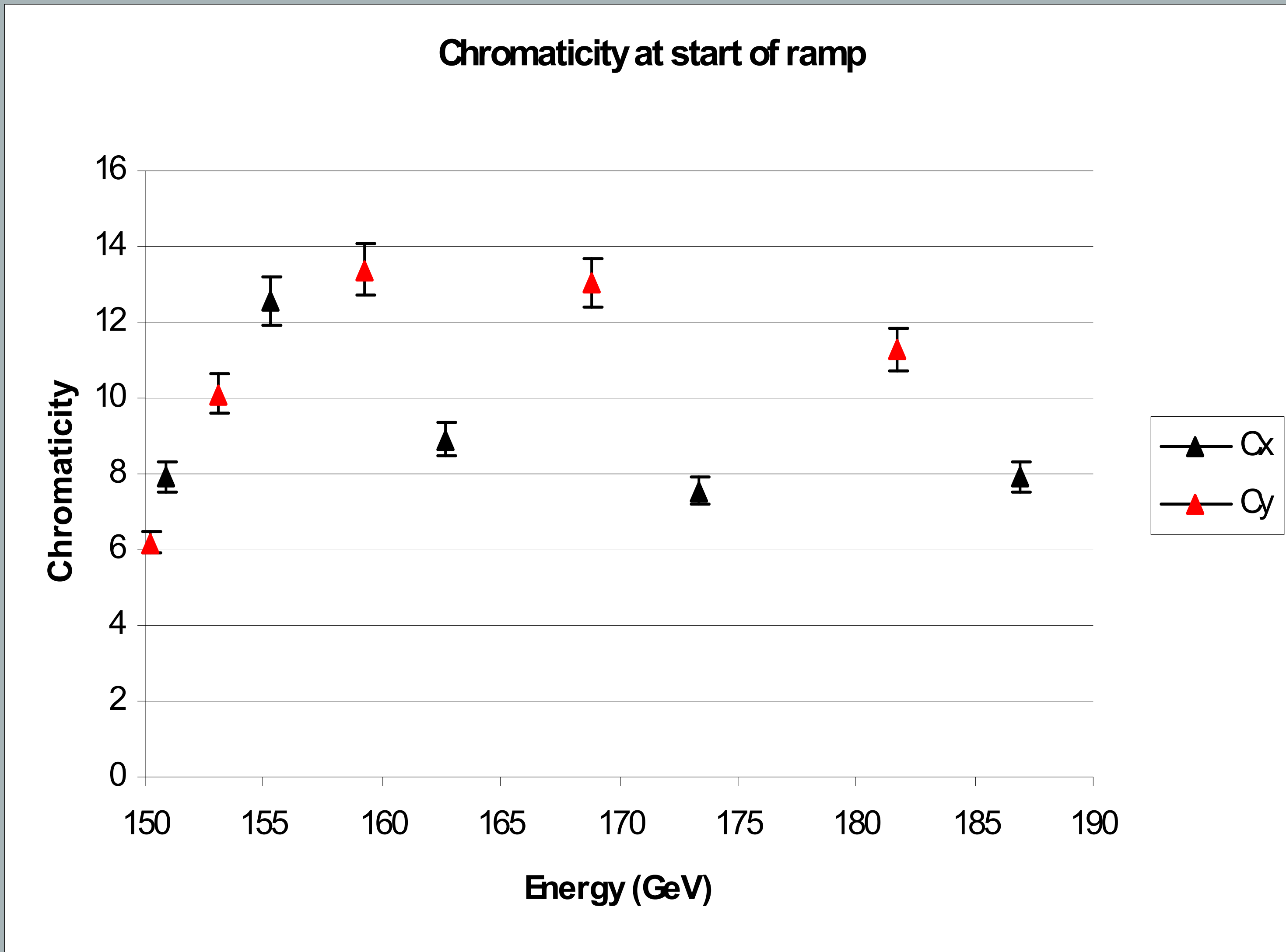
Comparison of Head-Tail with RF at 150 GeV for Horizontal Chromaticity



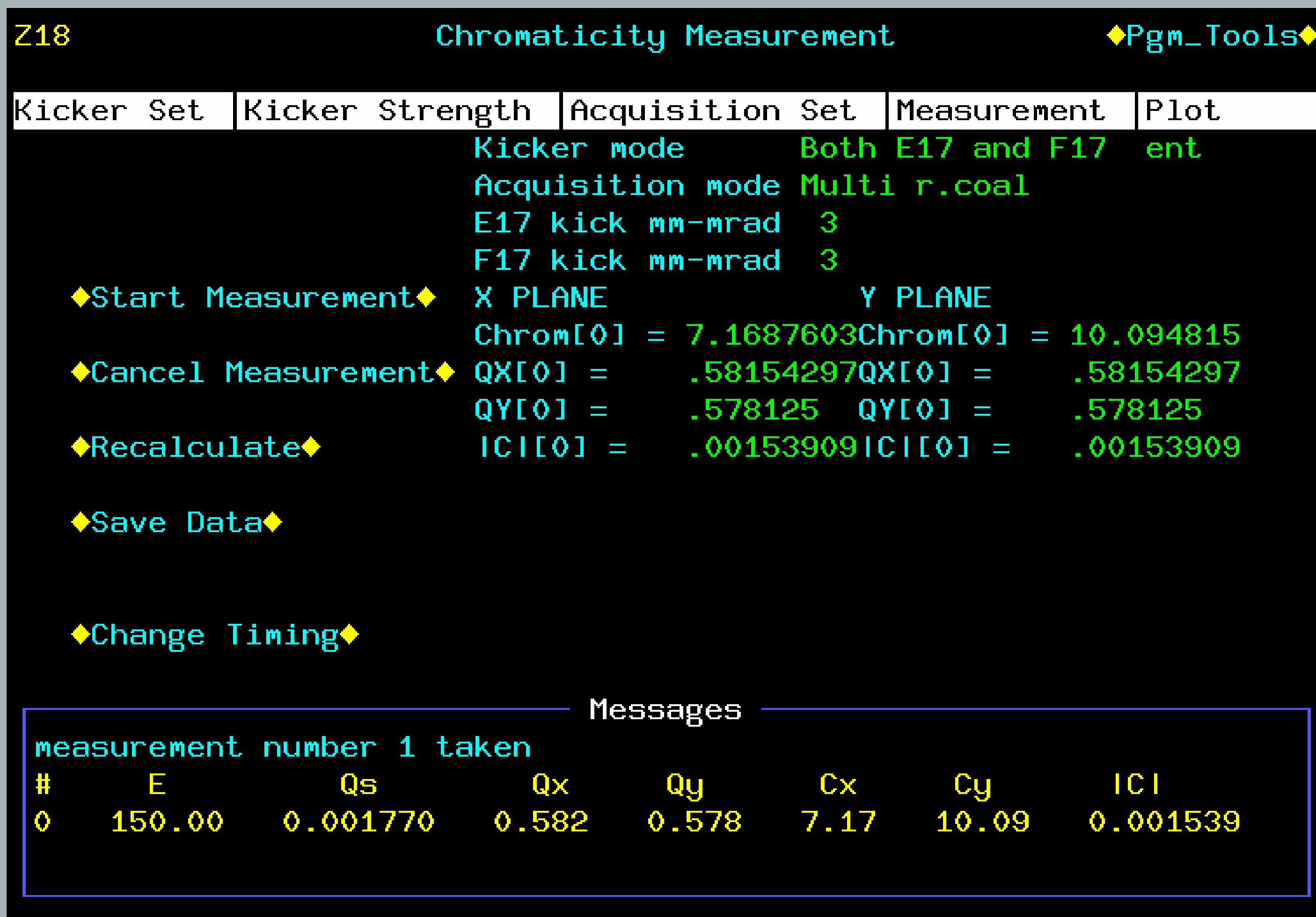
Comparison of Head-Tail with RF at 150 GeV for Vertical Chromaticity

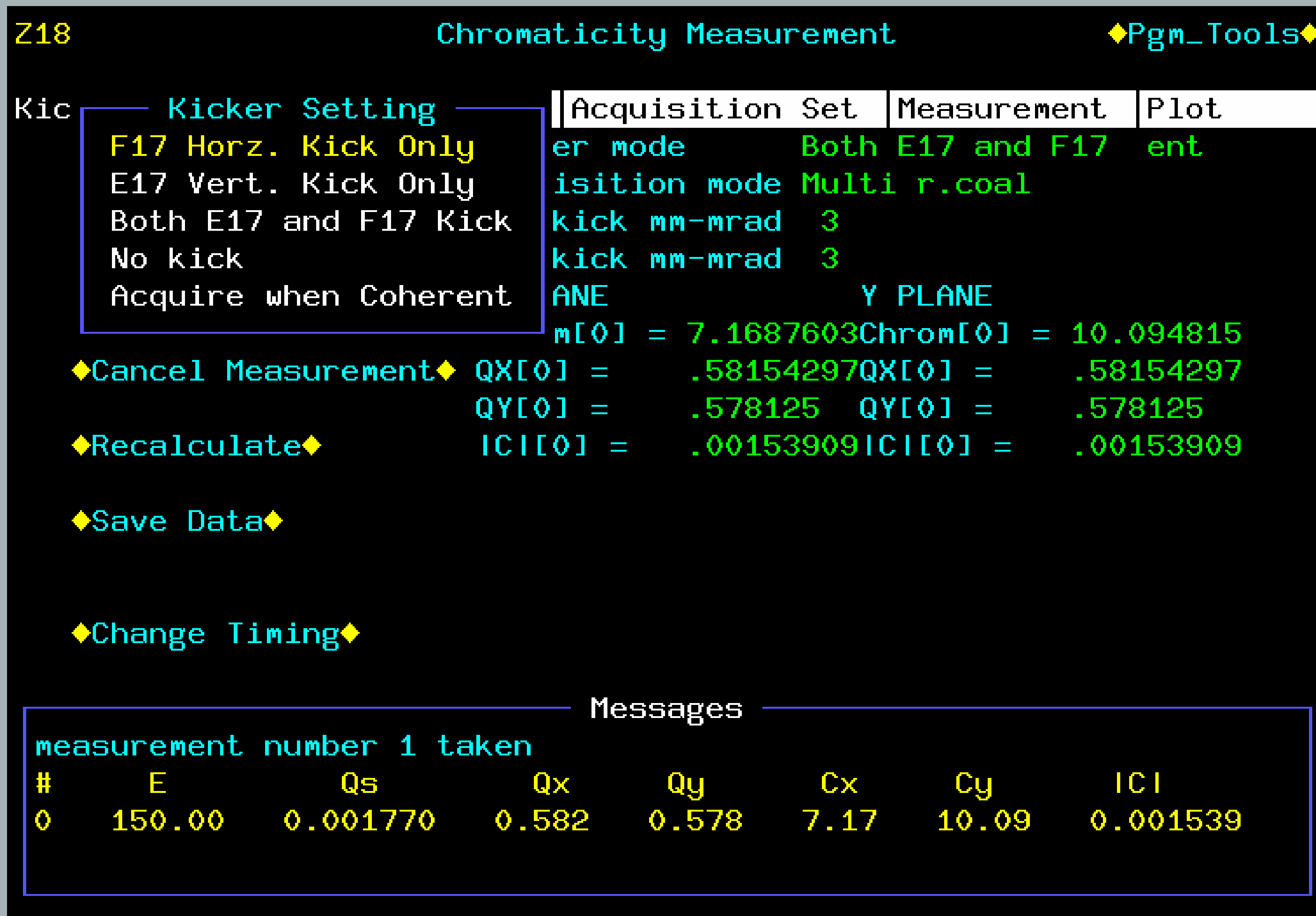


Results from test during Acceleration ramp



C100 Program




Z18
Chromaticity Measurement
♦Pgm_Tools♦
Kic
Kicker Setting
F17 Horz. Kick Only
E17 Vert. Kick Only
Both E17 and F17 Kick
No kick
Acquire when Coherent
Acquisition Set
Measurement
Plot
er mode Both E17 and F17 ent
isition mode Multi r.coal
kick mm-mrad 3
kick mm-mrad 3
ANE Y PLANE
m[0] = 7.1687603Chrom[0] = 10.094815
♦Cancel Measurement♦
QX[0] = .58154297QX[0] = .58154297
QY[0] = .578125 QY[0] = .578125
♦Recalculate♦
|C|[0] = .00153909|C|[0] = .00153909
♦Save Data♦
♦Change Timing♦
Messages
measurement number 1 taken
E Qs Qx Qy Cx Cy |C|
0 150.00 0.001770 0.582 0.578 7.17 10.09 0.001539

Z18 Chromaticity Measurement ◆Pgm_Tools◆

Kicker Set | Kicker St

Kicker Strength Settings at 150 GeV

E17 vert.kick [3] mm-mrad pi

F17 horz. kick [3] mm-mrad p

Return

◆Start Measurement◆

◆Cancel Measurement◆

◆Recalculate◆

◆Save Data◆

◆Change Timing◆

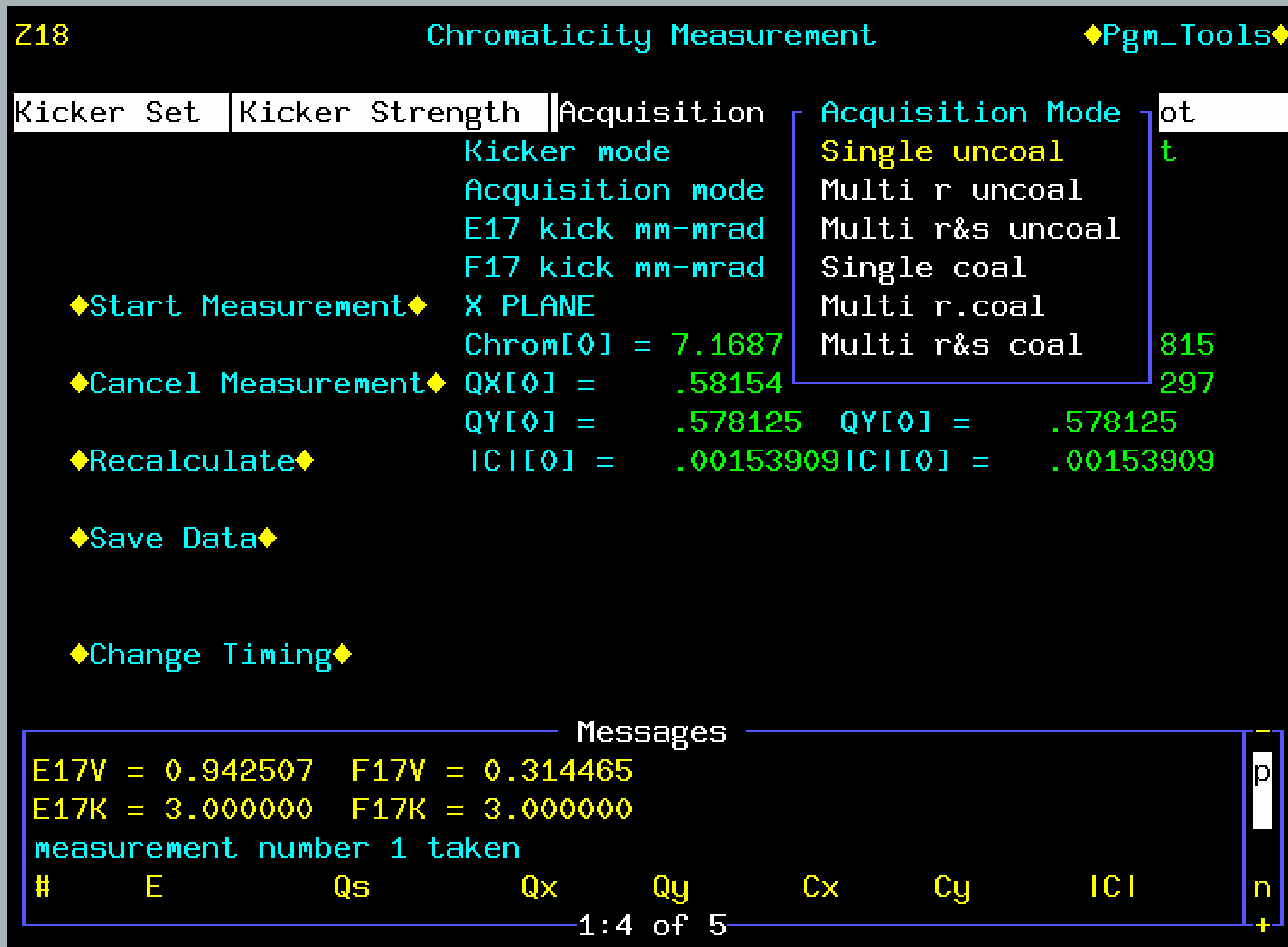
F17 kick mm-mrad 3

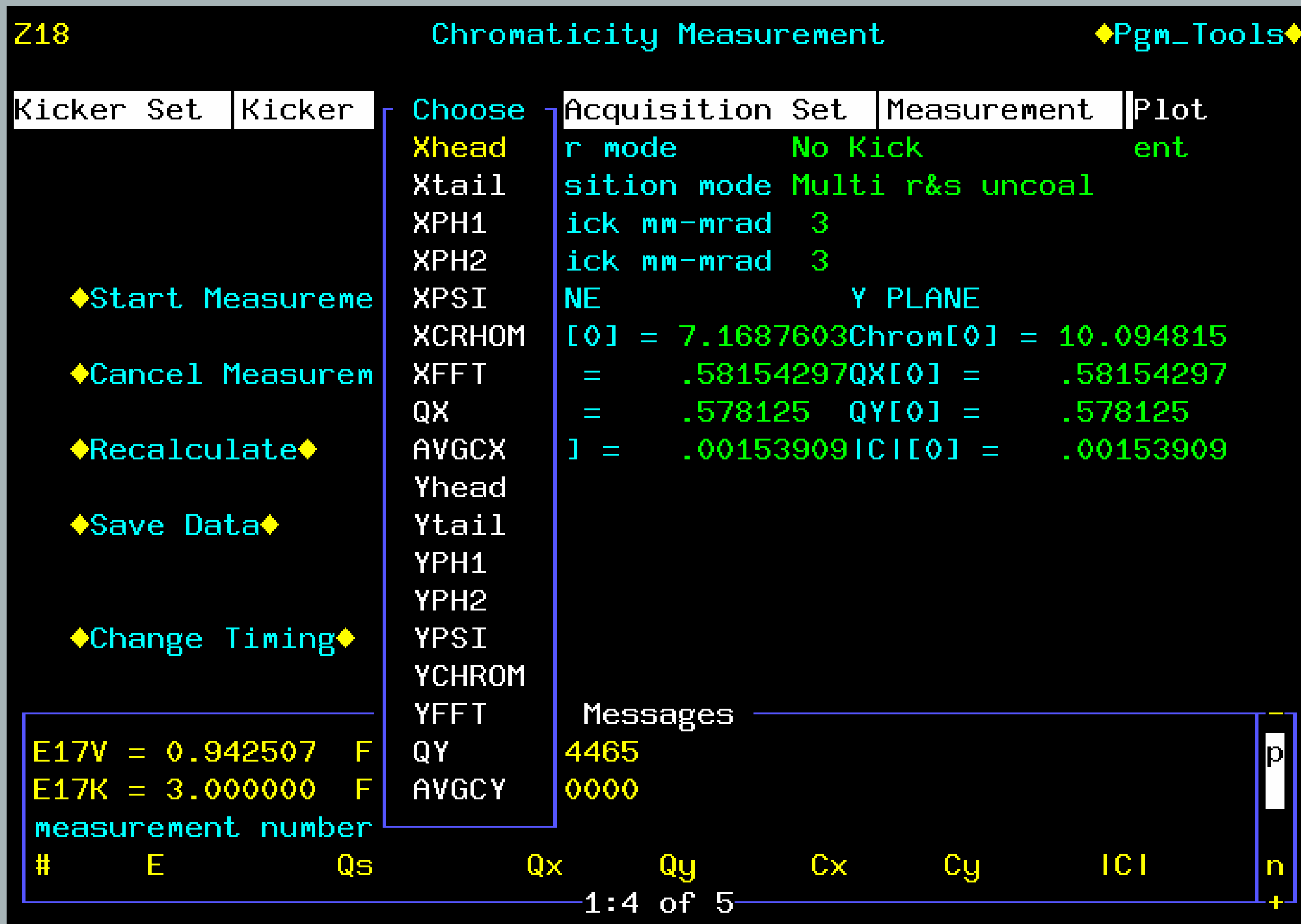
X PLANE		Y PLANE	
Chrom[0] =	7.1687603	Chrom[0] =	10.094815
QX[0] =	.58154297	QX[0] =	.58154297
QY[0] =	.578125	QY[0] =	.578125
|C|[0] =	.00153909	|C|[0] =	.00153909

Messages

measurement number 1 taken

#	E	Qs	Qx	Qy	Cx	Cy	|C|
0	150.00	0.001770	0.582	0.578	7.17	10.09	0.001539


Z18
Chromaticity Measurement
♦Pgm_Tools♦
Kicker Set
Kicker Strength
Acquisition
ot
Kicker mode
Acquisition mode
E17 kick mm-mrad
F17 kick mm-mrad
Acquisition Mode
Single uncoal
Multi r uncoal
Multi r&s uncoal
Single coal
Multi r.coal
Multi r&s coal
t
♦Start Measurement♦
X PLANE
Chrom[0] = 7.1687
815
♦Cancel Measurement♦
QX[0] = .58154
297
QY[0] = .578125 QY[0] = .578125
♦Recalculate♦
|C|[0] = .00153909|C|[0] = .00153909
♦Save Data♦
♦Change Timing♦
Messages
E17V = 0.942507 F17V = 0.314465
E17K = 3.000000 F17K = 3.000000
measurement number 1 taken
E Qs Qx Qy Cx Cy |C|
1:4 of 5
p
n


Z18
Chromaticity Measurement
◆Pgm_Tools◆
Kicker Set
Kicker
Choose
Acquisition Set
Measurement
Plot
Xhead
r mode
No Kick
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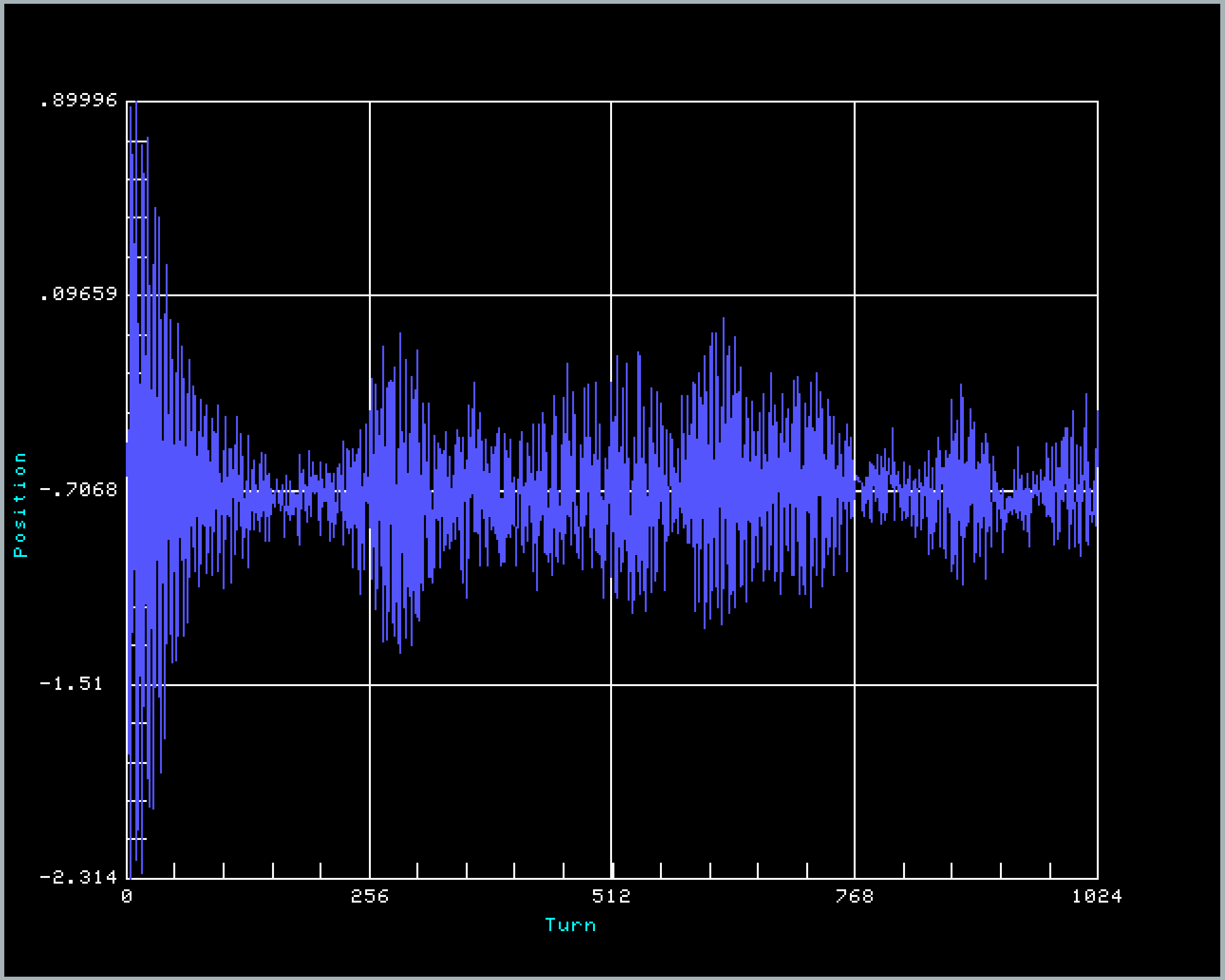
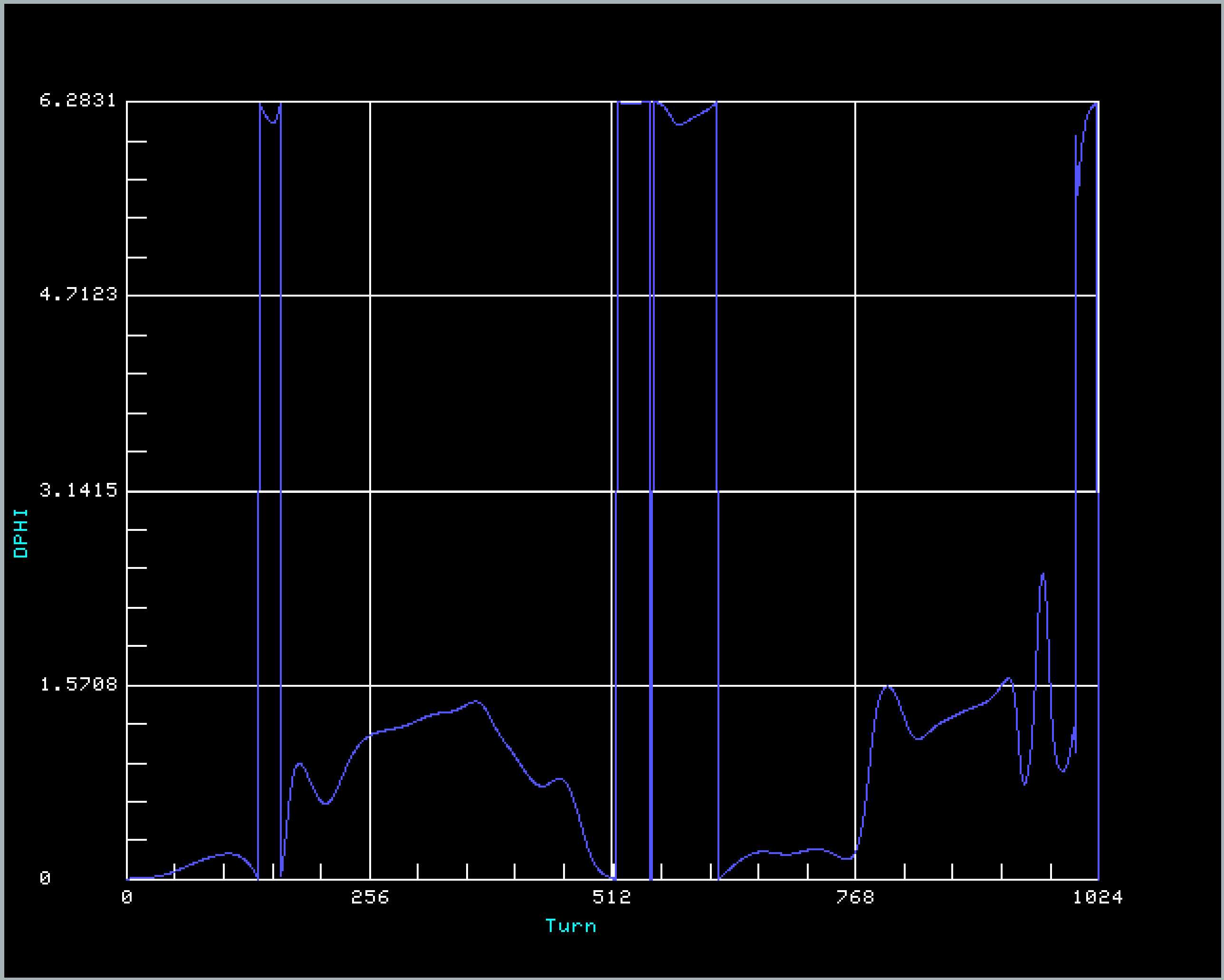
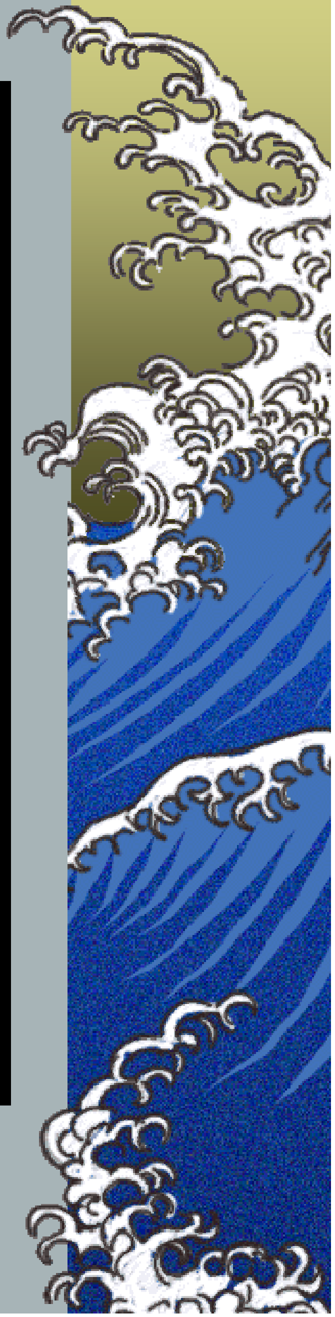
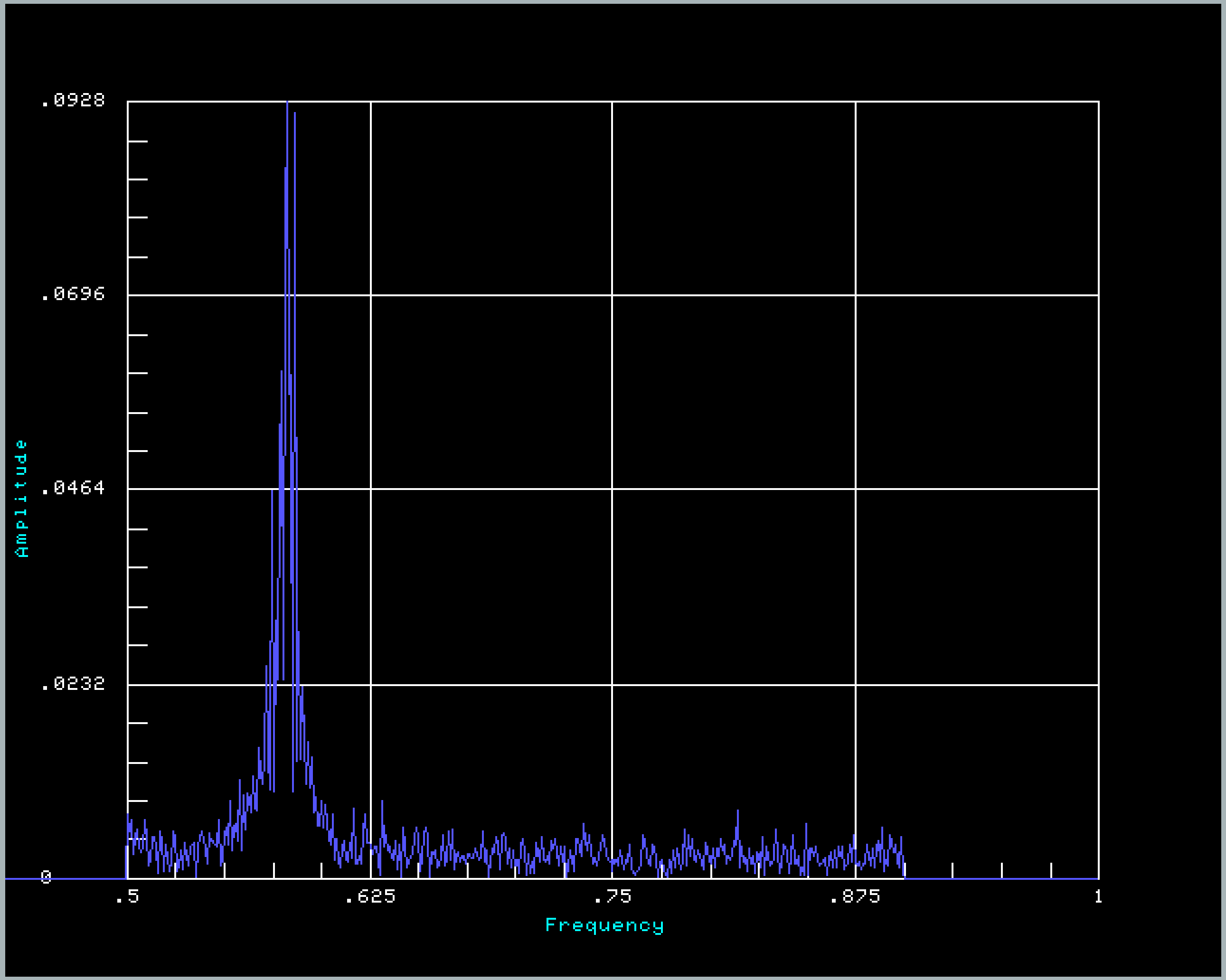
Xtail
sition mode Multi r&s uncoal
XPH1
ick mm-mrad 3
XPH2
ick mm-mrad 3
◆Start Measureme
XPSI
NE
Y PLANE
XCRHOM
[0] = 7.1687603Chrom[0] = 10.094815
◆Cancel Measurem
XFFT
= .58154297QX[0] = .58154297
QX
= .578125 QY[0] = .578125
◆Recalculate◆
AVGCX
] = .00153909|C|[0] = .00153909
Yhead
◆Save Data◆
Ytail
YPH1
YPH2
◆Change Timing◆
YPSI
YCHROM
YFFT
Messages
E17V = 0.942507 F
QY
4465
E17K = 3.000000 F
AVGCY
0000
measurement number
E Qs Qx Qy Cx Cy |C|
1:4 of 5


.89996
.09659
-.7068
-1.51
-2.314
Position
0
256
512
768
1024
Turn


6.2831
4.7123
3.1415
1.5708
0
DPHI
0
256
512
768
1024
Turn




.0928
.0696
.0464
.0232
0
Amplitude
.5
.625
.75
.875
1
Frequency

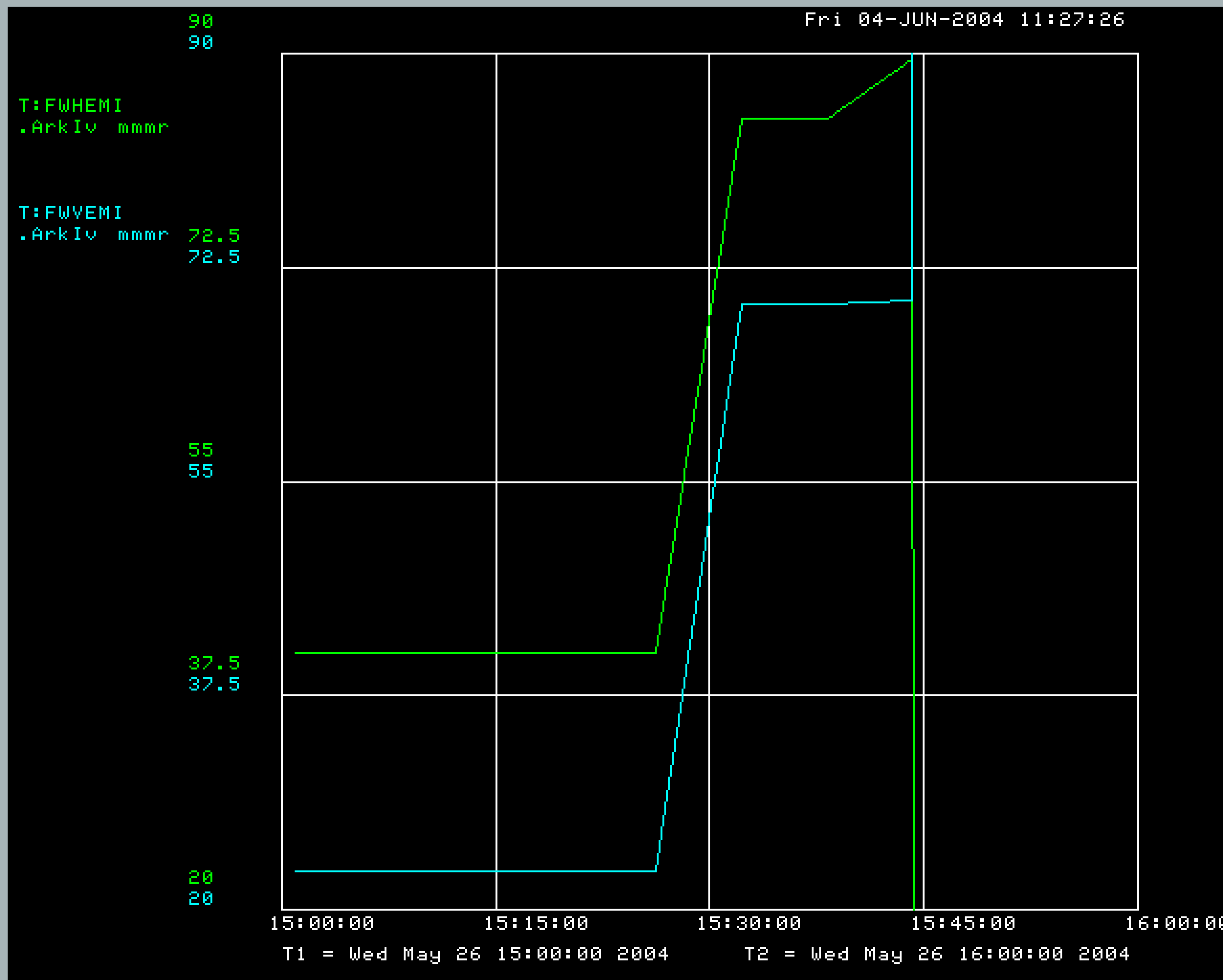
```
Z18                    Chromaticity Measurement                  ◆Pgm_Tools◆

Kicker Set | Kicker Strength | Acquisition Set | Measurement | Plot
                        Kicker mode      No Kick            ent
                        Acquisition mode Multi r&s uncoal
                        E17 kick mm-mrad  3
                        F17 kick mm-mrad  3
  ◆Start Measurement◆   X PLANE                Y PLANE
                        Chrom[0] = 7.1687603Chrom[0] = 10.094815
  ◆Cancel Measurement◆  QX[0] =    .58154297QX[0] =    .58154297
                        QY[0] =    .578125  QY[0] =    .578125
  ◆Recalculate◆         |C|[0] =   .00153909|C|[0] =   .00153909
                               Timing
  Single Sample Event [4C EVENT_TEV_SAMPLE                 ]
  Ramp Event          [42 EVENT_TEV_START_RAMP             ]
  Squeeze Event       [C5 EVENT_START_B0_SQUEEZE           ]
  E17timing           [.643     ]
  F17timing           [.051     ]
  E17delay            [1        ]                            -
  F17delay            [2.4965   ]                            p
  Time Step           [4        ]                          804
  Number of Points    [1        ]
  Bunch Number        [0        ]                          061 n
                               Return                          +
```

Limitations of current set-up

- *Destructive measurements*
  - *Emittance blow up, aperture limitations*
- *Tracking Phase over 2π*
- *Extracting usable signal*
  - *Phase contamination: coupling*
  - *Decoherence time: Tune spread*
    - *Linear chrom.*
    - *2nd order chrom*
    - *Octupoles*
    - *Impedance*
    - *beam intensity*
    - *rms bunch length*
    - *synchrotron tune.*

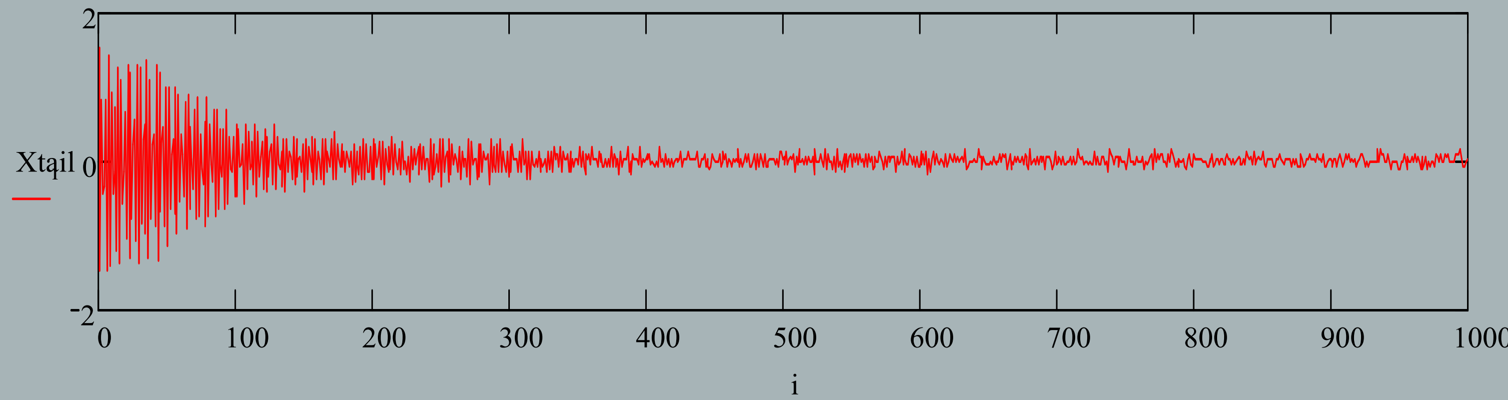
Emittance Blow up after 5 kicks in Horizontal and 5 kicks vertically

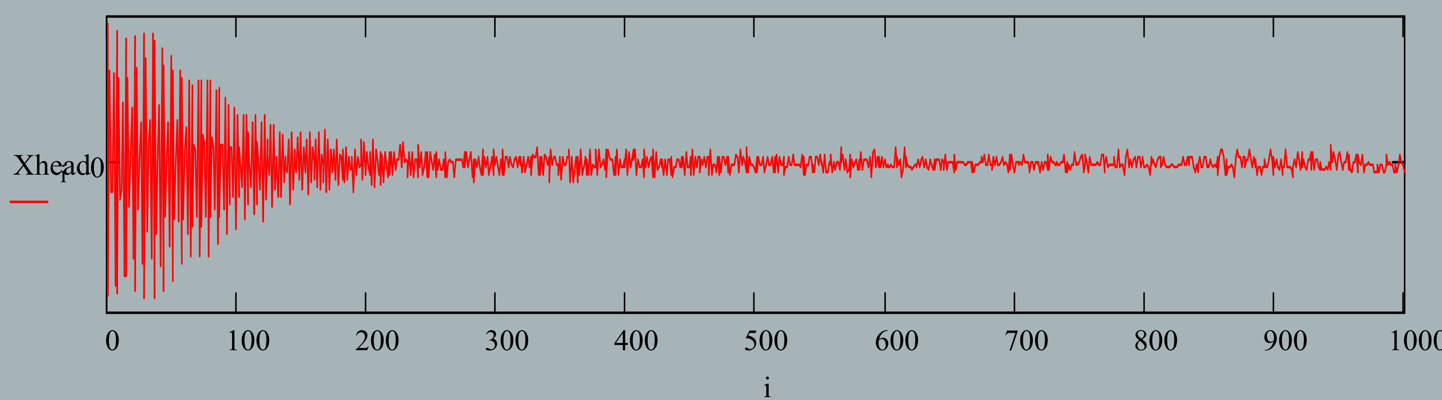


Decoherence time

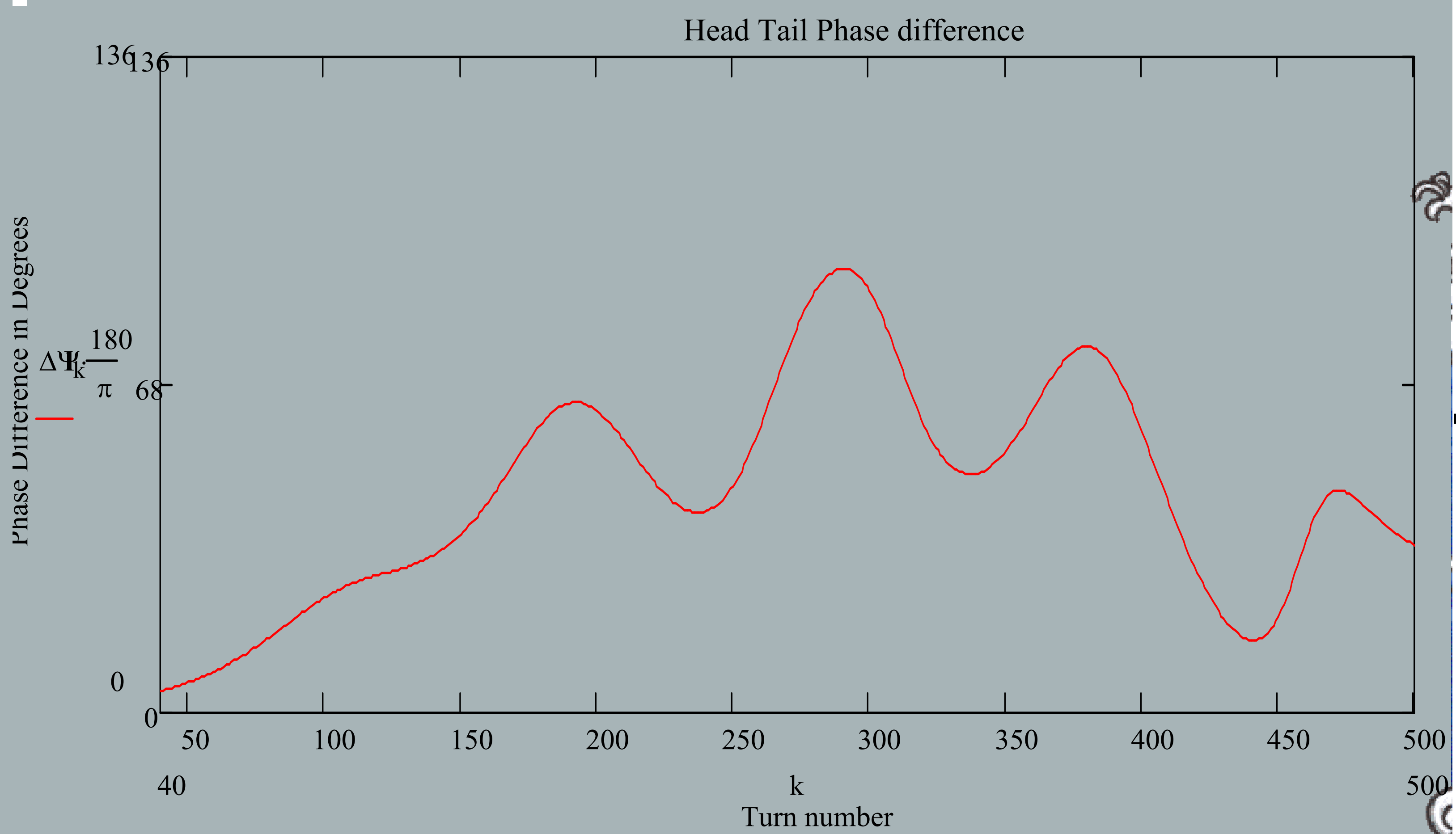
- Octupoles at Injection:
  - Damping time can be less than 100 turns
  - Effected by
    - bunch intensity (need > 280E+9) to get signal at 300 turns.
    - transverse emittance.
- Flat-top
  - high chromaticities
  - longer synchrotron periods

Head and Tail turn-by-turn vertical motion with strong Coupling and Octupoles on.





Less usable signal with faster decoherence time.



LHC and Tev Parameters[2]

	Tev Injection	*Tev Flattop*	*LHC Injection*	*LHC Flattop*
Energy (GeV)	*150*	*980*	*450*	*7000*
Revolution Frequency (kHz)	*47.7*		*11.245*	
Synchrotron Frequency (Hz)	*86*	*34*	*61.8*	*21.4*
rms bunch length (nsec)	*3*	*1.7*	*.37*	*.25*
Slip factor	*.0028*		*.0003*	
Bunch Intensity	*3e11*		*1e11*	
Aperture (mm)	*74*		*44*	

- *Synchrotron Period:*
  - *182 - 525 turns in LHC*
  - *564 – 1412 turns in Tev*
- *Chromaticity Range ξ*
  - *(2 to +/-50 units) in LHC initially later (+/- 15 units) need control to 0.5 units tolerance 5 units [3]*
  - *(0 to 25 units) in Tev*
- *2nd Order Chromaticity Range $\xi 2$*
  - *11,000 uncorrected in LHC [3]*
  - *~1500 in Tev*
- *Damping Time (LHC) [3]*
  - *8 turns at 50 units of Chrom, 130 turns at 10 units.*
  - *250 turns at collisions*
- *Maximum Chrom. Measurement (0 to 2π)*
  - *In Tevatron we reach our maximum for a two point measurement at 2.5 GHz at 20 units*
  - *In the LHC this will be 15 units at 2.5 GHz.*
- *Coupling at injection:$|C-| = 0.01$, FT 0.001[3]*

Measurement Issues in LHC

- *Larger swings in Chromaticity in the LHC*
  - *(> 50 unit swing during 30 sec snap back with only 80% control from feed forward). [4]*
- *Decoherence Time*
  - *High 2nd order chromaticity*
  - *Helped by a shorter synchrotron period..*
  - *With Chrom > 20 units becomes a problem*
- *Emittance blow-up*
  - *Use current current method of kicking beam ~ 1 mm will allow only ~ 10 kicks.*
- *Longitudinal Bunch Motion ?*
  - *This currently makes HT measurements in Tevatron with uncoalesced bunches very difficult.*

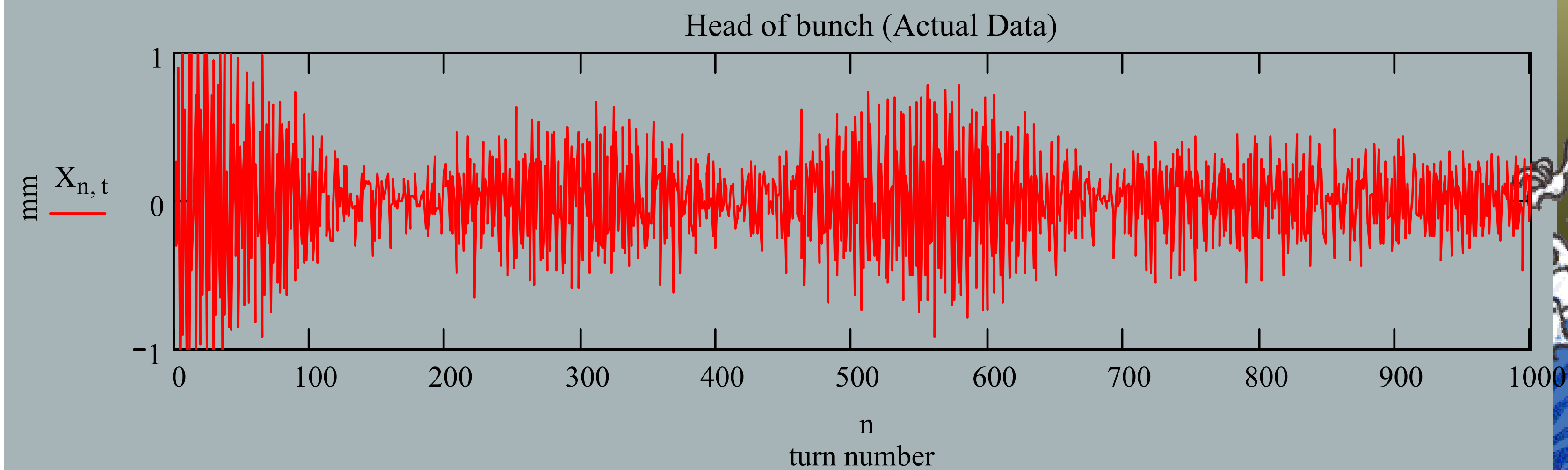
Possible Solutions and Plans for HT use in the LHC

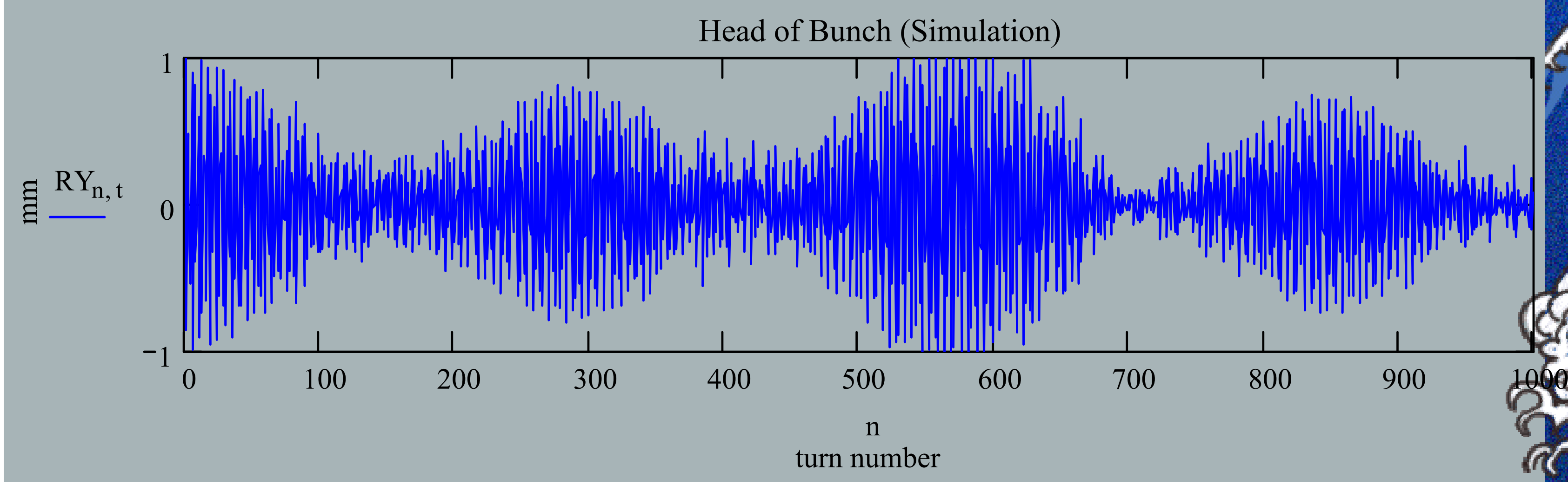
- *Large Chromaticities*
  - *damping time*
  - *Tracking phases > 360 degrees*
  - *Solution: Measure damping time or frequency width to grossly estimate large chromaticities.*
- *Damping Time and Emittance Blow up*
  - *Solution: Improve S/N by taking out the closed orbit offset in the signal*
    - *Auto-zeroing using variable attenuators*
    - *Using diodes : CERN guys now propose using a two diode system to measure top and bottom of doublet. To be tested in SPS next summer. (Perhaps we can try it now in the Tev?)*
- *The current plan for HT in LHC*
  - *Still in flux*
  - *Use PLL method for Q and Q' ?*
  - *Maybe be important for snap-back since it is possible to extract 10 measurements with tolerable beam blow-up.[3]*

Other Possible Measurements with HT monitor

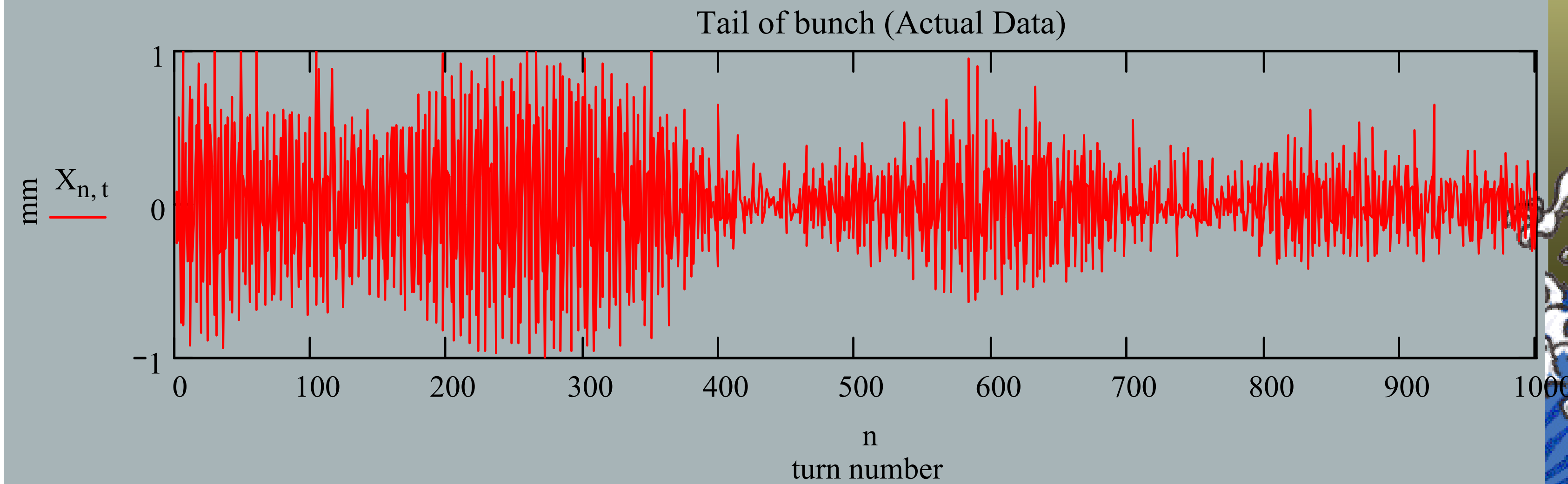
- *Measure Wake field strength?*
- *Measure 2nd Order Chromaticity?*
  - *Evolution of Beam Envelope over Bunch*
  - *Compare with multiparticle simulations*

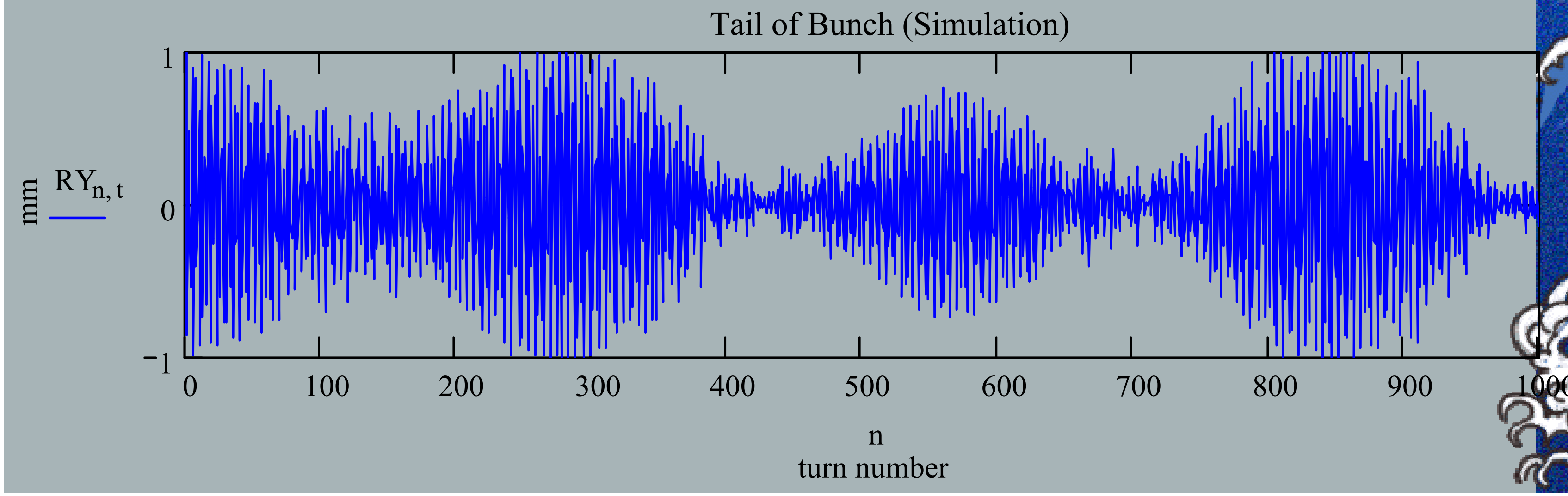
The Results of multi-particle simulation N=1000 particles with Resistive wall wake field 4.4E+5cm^{-1} (Z_{eff}=7 MΩ/m) ξ=3.733 total charge equal 2.6E+11 e . We did not include 2nd order chromaticity. The behavior is almost identical. Especially you can see larger re-coherence followed preceded by smaller one.



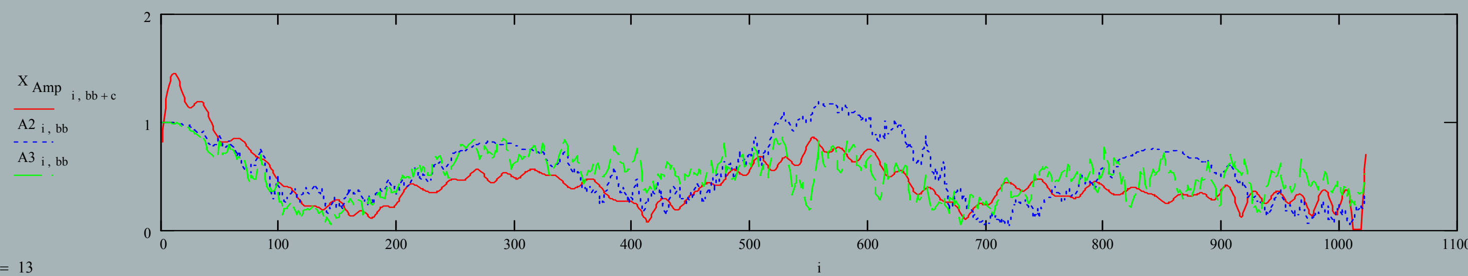


The tail of the bunch also displays a structure almost identical to the actual data. In fitting the data we found we could specify the strength of the resistive wall wake from 7E+5 cm^{-1} to 4.4E+5cm^{-1} (Z_{eff}=7-10 MΩ/m)

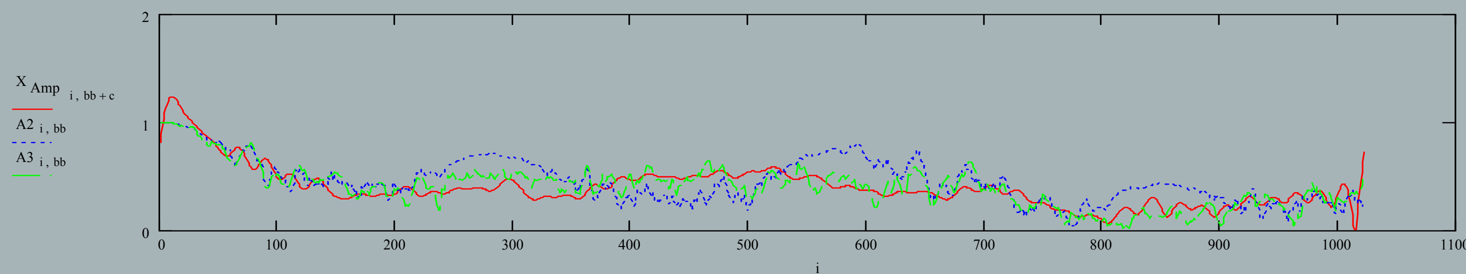




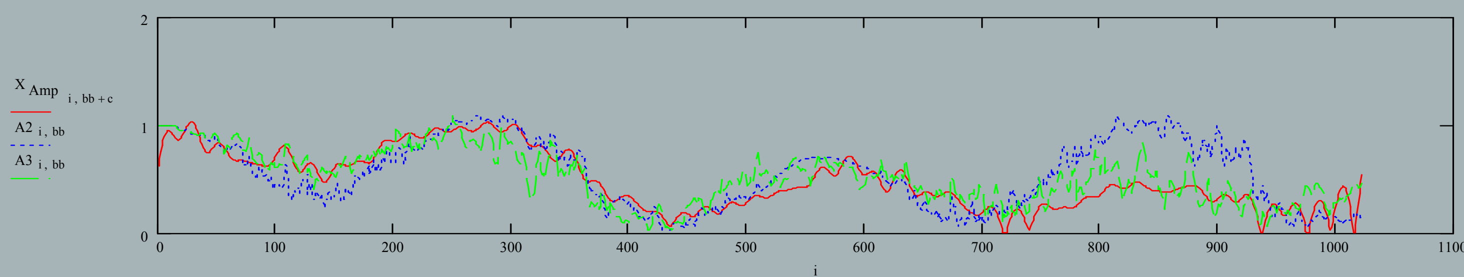
Now adding 2nd Order Chromaticity for a better fit.



bb := 13



bb := 3



Conclusion

- *Applying the HT Chromaticity in LHC will involve overcoming several issues*
  - *Emittance blow-up*
  - *Decoherence time*
  - *Tracking large Chromaticity swings*
  - *Coupling issues*
  - *Perhaps issues with longitudinal bunch motion?*
- *The information we get from the HT monitor can be mined to extract in addition to linear chromaticity, wake field strength, 2nd Order chromaticity and perhaps other effects at this stage these fits must be done offline but with more experience and perhaps using empirical model based on simulation.*

References:

[1] S. Fartoukh and R. Jones, LHC Project Report 602

[2] LHC Beam parameters and definitions (Vol 1. Chapter 2.)

[3] S. Fartoukh and J.P. Koutchouk,, LHC-B-ES-0004 rev 2.0 (2004)

[4] R. Jones, Beam measurement capabilities for controlling dynamic effects in the LHC (LHC Reference Magnetic System Review July 27th and 28th 2004)